Two Rare Magnetic Cataclysmic Variables with Extreme Cyclotron Features Identified in the Sloan Digital Sky Survey[1]

Paula Szkody[2], Scott F. Anderson[2], Gary Schmidt[3], Patrick B. Hall[4], Bruce Margon[5], Antonino Miceli[2], Mark SubbaRao[6], James Frith[2], Hugh Harris[7], Suzanne Hawley[2], Brandon Lawton[2], Ricardo Covarrubias[2], Kevin Covey[2], Xiaohui Fan[8], Thomas Murphy[2] Vijay Narayanan[4], Sean Raymond[2], Armin Rest[2], Michael A. Strauss[4], Christopher Stubbs[2], Edwin Turner[4], Wolfgang Voges[9], Amanda Bauer[6], J. Brinkmann[10], Gillian R. Knapp[4], Donald P. Schneider[11]

ABSTRACT

Two newly identified magnetic cataclysmic variables discovered in the Sloan Digital Sky Survey (SDSS), SDSSJ155331.12+551614.5 and SDSSJ132411.57+032050.5, have spectra showing highly prominent, narrow, strongly polarized cyclotron humps with amplitudes that vary on orbital periods of 4.39 and 2.6 hrs, respectively. In the former, the spacing of the humps indicates the 3rd and 4th harmonics in a magnetic field of ∼60MG. The narrowness of the cyclotron features and the lack of strong emission lines imply very low temperature plasmas and very low accretion rates, so that the

---

[1]Based in part on observations obtained with the Sloan Digital Sky Survey and with the Apache Point Observatory (APO) 3.5m telescope, which are owned and operated by the Astrophysical Research Consortium (ARC). A portion of the observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

[2]Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195

[3]The University of Arizona, Steward Observatory, Tucson, AZ 85721

[4]Princeton University Observatory, Peyton Hall, Princeton, NJ 08 544

[5]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

[6]Astronomy and Astrophysics Center, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637

[7]US Naval Observatory, Flagstaff, AZ 86002

[8]The Institute for Advanced Study, Princeton, NJ 08540

[9]Max-Planck-Institute für extraterrestrische Physik, Geissenbachstr. 1, D-85741 Garching, Germany

[10]Apache Point Observatory, PO Box 59, Sunspot, NM 88349

[11]Department of Astronomy & Astrophysics, Penn State University, University Park, PA 16802

accreting area is heated by particle collisions rather than accretion shocks. The detection of rare systems like these exemplifies the ability of the SDSS to find the lowest accretion rate close binaries.

Subject headings: cataclysmic variables — stars:individual (SDSSJ155331.12+551614.5, SDSSJ132411.57+032050.5)

1. Introduction

The commissioning year of the Sloan Digital Sky Survey (SDSS; York et al. 2000, Stoughton et al. 2002) showed that this survey is highly effective in finding new cataclysmic variables (Szkody et al. 2002). While previous surveys had primarily identified the brightest systems with the highest mass transfer rates, the SDSS photometry in 5 filters to well beyond 20th magnitude (Gunn et al. 1998, Fukugita et al. 1996, Hogg et al. 2001, Pier et al. 2002, Smith et al. 2002) is able to find the population of low mass transfer rate, very short orbital period systems that are predicted to exist in close binary evolution models (Howell, Rappaport & Politano 1997). Included in this latter group are some systems which contain highly magnetic white dwarfs with field strengths 6-240 MG which are termed AM Her systems, or polars (see Warner 1995 for a review of all types of cataclysmic variables).

In the polars, the high field prevents the formation of an accretion disk by directing the ballistic flow of material transferred from the late type secondary onto one or both magnetic poles of the white dwarf. Different regimes of accretion rate and magnetic field strength are predicted to result in quantitatively different accretion scenarios (Wickramasinghe & Ferrario 2000; WF2000). At the highest specific accretion rates (100 g cm^{-2} s^{-1}), high density blobs carry the mass and energy below the surface of the white dwarf. At mid accretion rates (1 g cm^{-2} s^{-1}), a standoff shock is formed above the surface and the gas cools primarily by 10-30 keV thermal bremsstrahlung emission. As the accretion lowers by another factor of 100, the cooling becomes dominated by cyclotron emission, until at the lowest rates, a shock does not form at all and the energy of the incoming ions is transmitted directly to the atmosphere of the white dwarf in what is termed a "bombardment solution" (Kuipers & Pringle 1982). The magnetic field also affects the results in that higher fields tend to produce weaker shocks and possibly more direct heating by blobs beneath the surface (Ramsay et al. 1994). Complicating this picture further is the fact that the accretion rate of polars can sporadically change. Typically, sytems in high mass-transfer states exhibit strong HeII λ4686 and Balmer emission lines which dominate the optical spectrum, and strong X-ray and cyclotron emission. At low states of reduced or absent mass transfer, the line emission disappears (except for some narrow Balmer emission from the irradiated secondary star), the X-ray and cyclotron emission is much reduced or absent, and the photospheres of the white dwarf and late secondary are visible.

During low states, the magnetic field may be identified through Zeeman splitting in the photospheric spectrum, but for most systems, the field is determined in high states of accretion from the presence of cyclotron harmonics in the optical and near-IR. Cyclotron opacity is a rapidly decreasing function of harmonic number, and the high harmonics are strongly angle-dependent, polarized, and broadened with increasing electron temperature (e.g. Chanmugam 1980; Meggitt & Wickramasinghe 1982). For T<10 keV, the wavelength of the harmonic number n is simply related to the magnetic field B: $\lambda_n = (10,700)/n)(10^8/B)$ Å.

Within the above theoretical and empirical framework, observation of the soft and hard X-ray fluxes, and of the optical spectral and cyclotron features, can elucidate the magnetic field and accretion regime of identified polars. More than 80% of the $\sim$ 65 known polars were discovered in the ROSAT All Sky Survey (RASS; Voges et al. 1999), with typical count rates for 15-19th optical magnitudes in the range of 0.2-2.5 c/s (Beuermann & Burwitz 1995). The selection criteria of high X-ray count rate and strong optical emission lines resulted in the discovery of polars in the middle to high specific accretion rate regimes. Recently, the deep objective prism plates of the Hamburg Quasar survey provided the identification of 2 polars with extremely low accretion rates (WX LMi = HS 1023+3900; Reimers, Hagen & Hopp 1999, and HS 0922+1333; Reimers & Hagen 2000) and the followup of faint ROSAT sources yielded two more (RX J012851.9-233931; Schwope, Schwarz & Greiner 1999, and RX J1007.5-2016; Reinsch et al. 1999). In this paper, we describe 2 new SDSS polars which are among the most extreme cases of the intriguing cyclotron-dominated systems at the lowest accretion rates. As only a small fraction of the eventual SDSS data have been examined, the survey should discover a modest-sized sample of these previously exotic stars.

2. Observations

The objects SDSSJ155331.12+551614.5 (hereafter abbreviated SDSS1553) and SDSSJ132411.57+032050.5 (hereafter SDSS1324) were automatically selected for SDSS spectroscopy since their unusual SDSS colors (r=17.43, $u-g$=1.52, $g-r$=1.06, $r-i$=0.40, $i-z$=1.00 for SDSS1553 and r=20.44, $g-r$=1.65, $r-i$=0.21, $i-z$=0.83, $u-g$ $\sim$1.1 for SDSS1324 with no reddening correction) fell far from the stellar locus and within the selection criteria for quasars (Richards et al. 2002). The SDSS spectra with $\sim$3Å resolution

(Figure 1), show strong broad cyclotron features at 4600Å and 6200Å in SDSS1553 and at 5700Å in SDSS1324 together with the TiO band features of late-type main-sequence stars. Periodic photometric variability at different wavelengths (Figure 2) was used to determine the orbital periods. Observations were obtained with the United States Naval Observatory (USNO) 1m telescope using BVRI filters calibrated with Landolt standards, with the University of Washington Manastash Ridge Observatory (MRO) 0.76m telescope with a 1024×1024 pixel Ford Aerospace CCD, using a filter similar to the Sloan r ($\lambda_c \sim 6230$Å) and a Harris V filter, and with the Apache Point Observatory (APO) 3.5m using the 2048×2048 pixel SITe CCD system SPIcam with the Sloan r filter. Follow-up spectroscopic observations were conducted on SDSS1553, using the Double Imaging Spectrograph (DIS) on the APO 3.5m telescope at low resolution (∼12Å) with a 1.5″ slit, providing flux-calibrated data from 3800−9200Å. These observations showed that the cyclotron features are highly variable throughout the orbital period (Figure 3). Finally, to confirm the suspected magnetic nature of the objects, circular polarization observations were obtained with the CCD Spectropolarimeter SPOL on the 6.5m MMT and on the Steward Observatory 2.3m telescope (Figures 4 and 5). SPOL was used with a low-resolution grating and a 1.1″ slit, providing spectral coverage of ∼4200−8400Å at a resolution of ∼15Å. Observations for both objects are summarized in Table 1.

3. SDSS1553

The nights of MRO and USNO photometry (Figure 2) reveal periodic, highly modulated light curves. The spectrum (Figure 1) indicates that the r, R and V filter passbands are dominated by the strong 6200Å harmonic, while the B filter contains the 4600Å harmonic. The I band shows only a 0.15 mag modulation, which may be due to a harmonic near 9200Å (see below). The best period determined from combining the 5 nights of r data is 0.18297±0.00004d (4.39 hr) and Figure 2 shows the data phased on this period (with arbitrary zero phase using the first photometric data point at JD2452164.73522). The sinusoidal shape of the light curve implies we are seeing the geometrical change associated with the changing viewing angle of a single magnetic pole that is not self-eclipsed by the white dwarf i.e. i (angle of rotation axis to the line of sight) + β (angle between rotation axis and the magnetic pole) $<90°$.

With this period, we were able to phase the spectroscopic data into an orbital sequence (Figure 3) which shows the changing amplitude of the cyclotron features. The spacing, the large amplitudes, and the narrow and asymmetric profiles of these features are all indicative of cyclotron emission at low electron temperatures (WF2000). The hump locations are consistent with cyclotron harmonics n=3 (6200Å) and n=4 (4600Å) in a magnetic field near 58 MG. The narrow widths imply $T_e \leq 5$ keV. The circular polarization spectrum (Figure 4) confirms this conclusion by showing that the features are highly polarized and the large difference in polarization between the 6200Å and 4600Å features shows that the emission changes from marginally optically thick at n=3 to thin at n=4.

It is clear that SDSS1553 has accretion characteristics that are unlike the majority of polars (WD2000). We derived an upper limit of 0.04 c/s from the RASS, and this lack of strong X-rays supports a low accretion rate, while the lack of strong Balmer emission lines indicates a greatly reduced ionizing UV flux (Liebert et al. 1978). It is apparent that the strength of Hα is anti-correlated with the strength of the cyclotron humps, indicating that its origin is likely on the irradiated secondary, as is common in polars with low mass transfer (Schmidt et al. 1981). Time-resolved spectropolarimetry at higher spectral resolution will ultimately be able to determine the viewing and magnetic geometry. While the cyclotron features of most polars show maximum strength when viewed perpendicular to the field lines and maximum circular polarization when viewed along the field lines, the angle dependence of the two is expected to be more similar at low optical depth and lower harmonic number (WF2000). This is borne out, in part, in the low $\dot{M}$ system RX J1007.5-2016 (Reinsch et al. (1999) where the cyclotron features are at highest intensity when viewed along the field lines.

While many polars show temporary low accretion states, the cyclotron humps present during those low states still indicate high temperature and optical depth (e.g. VV Pup; Visvanathan & Wickramasinghe 1979). SDSS1553 appears to belong to a rare group of polars with extremely low accretion rates ($\sim 10^{-13} M_\odot$ yr^{-1}), plasma temperatures (<5 keV), and specific accretion rates (10^{-3} g cm^{-2} s^{-1}) as described by Schwope et al. (1999). These conditions place these polars within the bombardment solution of heating by particle collisions rather than shocks. SDSS1553 and HS 0922+1333 (Reimers & Hagen 2000) appear to be the most extreme members of this group, based on their lack of X-rays and similarity of cyclotron features, while the others (WX LMi, RX J012851.9-233931, RX J1007.5-2016) have some X-ray emission and/or weaker and broader cyclotron harmonics.

Using SDSS template stars of late spectral class (Hawley et al. 2002), the TiO band strengths were used to identify an M5V star in SDSS1553. Using the mean $i - J$ color of +2.73 for M5 stars in the Early Data Release together with an absolute J magnitude of +9.38 and a measured Sloan i of +17.2, we infer a distance modulus for SDSS1553 in Sloan i of +5.1, or a distance of 100 pc.

Subtracting the M5V secondary from the APO spectra reveals the expected n=2 cyclotron harmonic near ∼9200Å. With the secondary as well as the large cyclotron features removed, the remaining flux was matched to the flux of DA white dwarfs at various temperatures (Hubeny & Lanz 1995), with radius of 8×10^8 cm and distance of 100 pc. This gave an upper limit of 10,000K to the temperature of the underlying white dwarf, assuming no continuum contribution from the cyclotron emission. Polars with periods $>$ 3 hrs generally have white dwarfs with temperatures $\geq$20,000K (Sion 1999). Thus, it appears that SDSS1553 contains a very cool white dwarf or, alternatively, its radius could be unusually small ($M \gtrsim 0.6M_\odot$). It is interesting that HS 0922+1333, with a period of 4.1 hrs, also appears to contain a cool white dwarf (Reimers & Hagen 2000).

4. SDSS1324

Although SDSS1324 is a much fainter object, with greater noise in the spectrum and spectropolarimetry, it appears to present an even more extreme example of a low accretion-rate system. The spectrum (Figure 1) is dominated by a large amplitude, narrow cyclotron feature near 5700Å and a second possible feature at 4250Å. These could be the 3rd and 4th harmonics in a field near 63 MG. The spectropolarimetry (Figure 5) shows the 5700Å feature is highly circularly polarized. As in SDSS1553, the r light curve of SDSS1324 shows a sinusoidal modulation of high amplitude (1.3 mag amplitude) on a 2.6 hr timescale, likely indicating a large modulation of the cyclotron feature throughout the orbit. Once again, the underlying contribution from the white dwarf must be very small. We derive an upper limit of 0.02 c/s from the RASS, even lower than SDSS1553.

5. Conclusions

Our photometry, spectroscopy and polarimetry of the SDSS source SDSS1553 have revealed a polar system with an orbital period of 4.39 hr. The spectrum is dominated by extreme amplitude, highly polarized cyclotron harmonics near 6200Å and 4600Å, indicating a white dwarf magnetic field strength of 58 MG, and TiO features from an M5V secondary star, indicating a distance of 100 pc. Similar cyclotron features and photometric variability in SDSS1324 indicate a polar with an orbital period near 2.6 hr. The narrowness and extreme amplitude of the cyclotron features imply that these systems are in the regime of low plasma temperature and very low specific accretion rate (the bombardment solution) where the accreting area is heated by particle collisions and the accretion luminosity appears as cyclotron radiation. The low count rates in the RASS (<0.04 c/s) support this view. With its ability to probe a wide variety of stellar systems, the SDSS is contributing to a less biased view of the conditions in polars, especially at low mass transfer rates.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/. Studies of magnetic stars and stellar systems at Steward Observatory is supported by the NSF through AST 97-30792. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Princeton University, the United States Naval Observatory, and the University of Washington.

REFERENCES

Beuermann, K. & Burwitz, V. in ASP Conf. Ser. 85, Cape Workshop on Magnetic Cataclysmic Variables, ed. D. A. Buckley & B. Warner (San Francisco:ASP), 99

Chanmugam, G. 1980, ApJ, 241, 1122

Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K. & Schneider, D. P. 1996, AJ, 111, 1748

Gunn, J. E. et al. 1998, AJ, 116, 3040

Hawley, S. L. et al. 2002, AJ, 123, 3409

Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J. & Gunn, J. E. 2001, AJ, 122, 2129

Howell, S. B., Rappaport, S. & Politano, M. 1997, MNRAS, 287, 929

Hubeny, I. & Lanz, T. 1995, ApJ, 439, 875

Kuijpers, J. & Pringle, J. E. 1982, A&A, 114, L4

Liebert, J., Stockman, H. S., Angel, J.R.P., Woolf, N.J., Hege, K. & Margon, B. 1978, ApJ, 225, 201

Meggitt, S. M. A. & Wickramasinghe, D. T. 1982, MNRAS, 198, 71

Pier, J. R. et al. 2002, AJ, submitted

Ramsay, G., Mason, K. O., Cropper, M., Watson, M. G. & Clayton, K. L. 1994, MNRAS, 270, 692

Reimers, D. & Hagen, H.-J. 2000, A&A, 358, L45

Reimers, D., Hagen, H.-J. & Hopp, U. 1999, A&A, 343, 157

Reinsch, K., Burwitz, V., Beuermann, K. & Thomas, H-C. 1999, ASP Conf. Ser. 157, Annapolis Workshop on Magnetic Cataclysmic Variables, eds. C. Hellier and K. Mukai, 187

Richards, G. T. et al. 2002, AJ, in press

Schmidt, G. D., Stockman, H. S. & Margon, B. 1981, ApJ, 243, L157

Schwope, A. D., Schwarz, R. & Greiner, J. 1999, A&A, 348, 861

Sion, E. M. 1999, PASP, 111, 532

Smith, J. A. et al. 2002, AJ, 123, 2121

Stoughton, C. et al. 2002, AJ, 123, 485

Szkody, P. et al. 2002,AJ, 123, 430

Visvanathan, N. V. & Wickramasinghe, D. T. 1979, Nature, 281, 47

Voges, W. et al. 1999, A&A, 349, 389

Warner, B. 1995 in Cataclysmic Variable Stars (Cambridge: CUP)

Wickramasinghe, D. & Ferrario, L. 2000, PASP, 112, 873: WF2000

York, D. G. et al. 2000, AJ, 120, 1579

This preprint was prepared with the AAS LaTeX macros v4.0.

Table 1. Summary of Observations

SDSS	UT Date	Obs	Data	Exp (min×Num)	Length (hr)
1553	2001 Mar 23	SDSS	ugriz	1×1	0.02
1553	2001 May 26	SDSS	Spectrum	87×1	1.5
1553	2001 Sept 2	APO	DIS Spectra	10-20×2	0.5
1553	2001 Sept 3	APO	DIS Spectra	10-15×3	0.6
1553	2001 Sept 4	APO	DIS Spectra	10-15×2	0.4
1553	2001 Sept 12	MRO	CCD filter r	5×5	2.7
1553	2001 Sept 12	APO	DIS Spectra	10×3	0.8
1553	2001 Sept 14	MRO	CCD filter r	5×10	5.0
1553	2001 Sept 15	MRO	CCD filter r	5×57	5.3
1553	2001 Sept 15	USNO	CCD BVRI	1-3×6	1.8
1553	2001 Sept 17	MRO	CCD filter V	5-10×30	3.9
1553	2001 Sept 18	APO	DIS Spectra	10×9	1.9
1553	2001 Sept 19	APO	DIS Spectra	10×13	2.4
1553	2001 Sept 20	MRO	CCD filter r	5×5	4.7
1553	2001 Sept 21	MRO	CCD filter r	5×9	0.8
1553	2001 Sept 21	USNO	CCD BVRI	1-3×7	2.1
1553	2001 Sept 25	USNO	CCD BVRI	1-3×8	2.1
1553	2002 Feb 7	APO	DIS Spectra	10×3	1.8
1553	2002 Feb 19	MMT	SPOL	24×1	0.4
1324	2002 May 5	SDSS	ugriz	1×1	0.02
1324	2002 Mar 8	SDSS	Spectrum	85×1	1.4
1324	2002 Mar 24	APO	CCD filter r	10×14	3.5
1324	2002 Mar 30	APO	CCD filter r	10×21	4.2
1324	2002 May 8	SO	SPOL	20×7	2.2

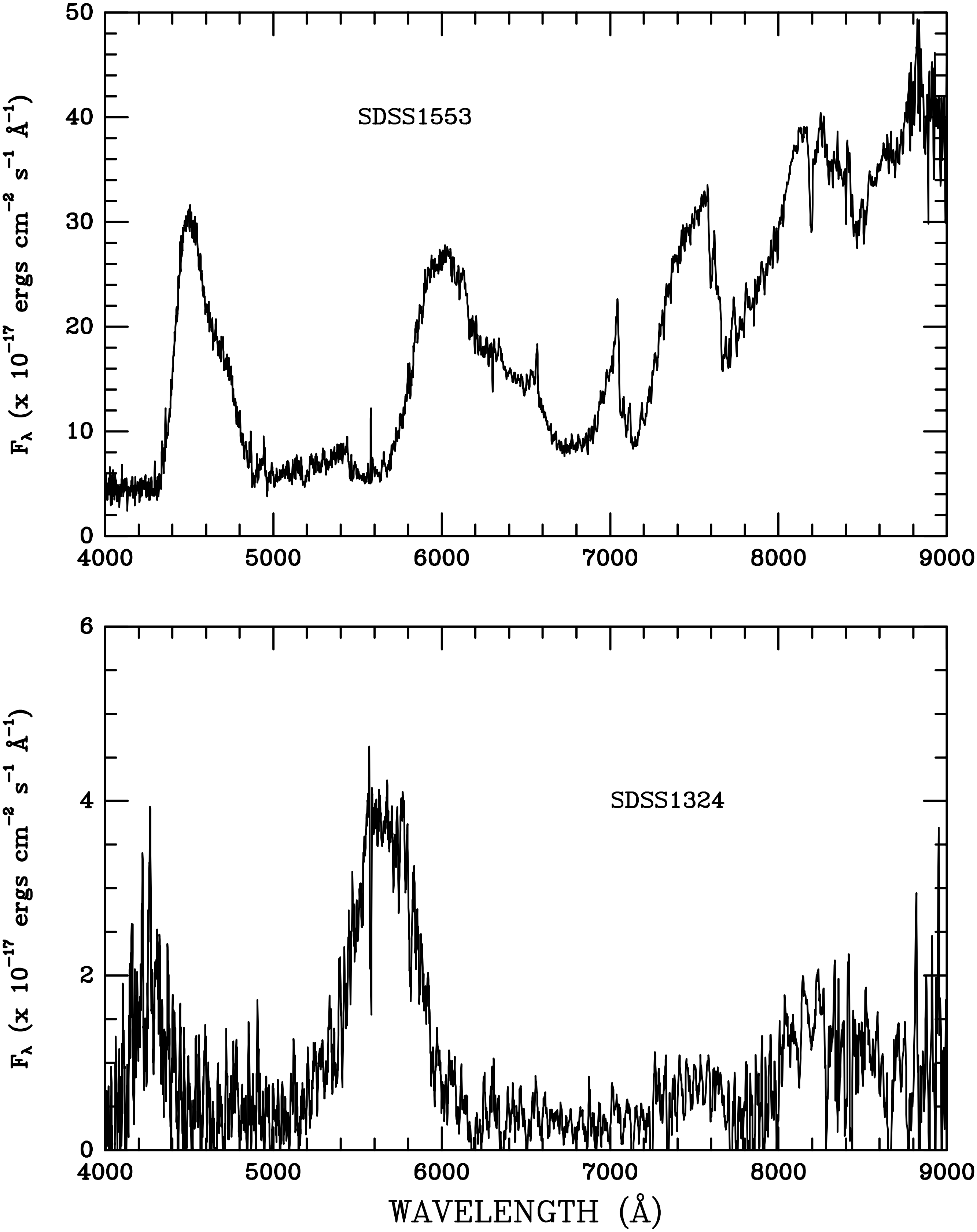
Fig. 1.— SDSS spectra of the newly discovered Polars. SDSS1553 has been smoothed with a running 3 point boxcar and SDSS1324 with a 9 point boxcar.

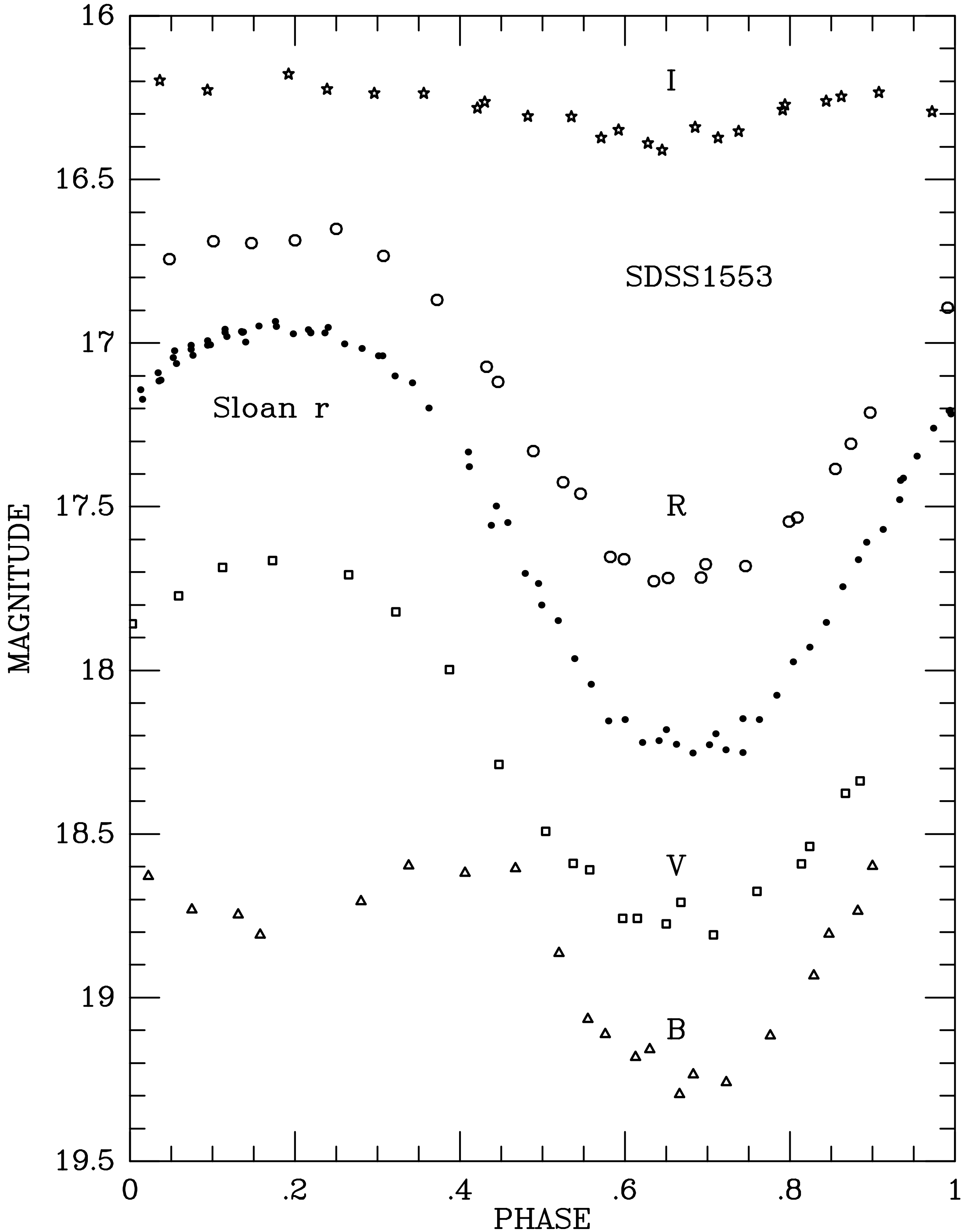
Fig. 2.— Light curves of SDSS1553 folded on the orbital period of 4.39 hrs. The Sloan r covers MRO data from Sept. 12-21 while the BVRI data are USNO data from Sept. 15, 21 and 25.

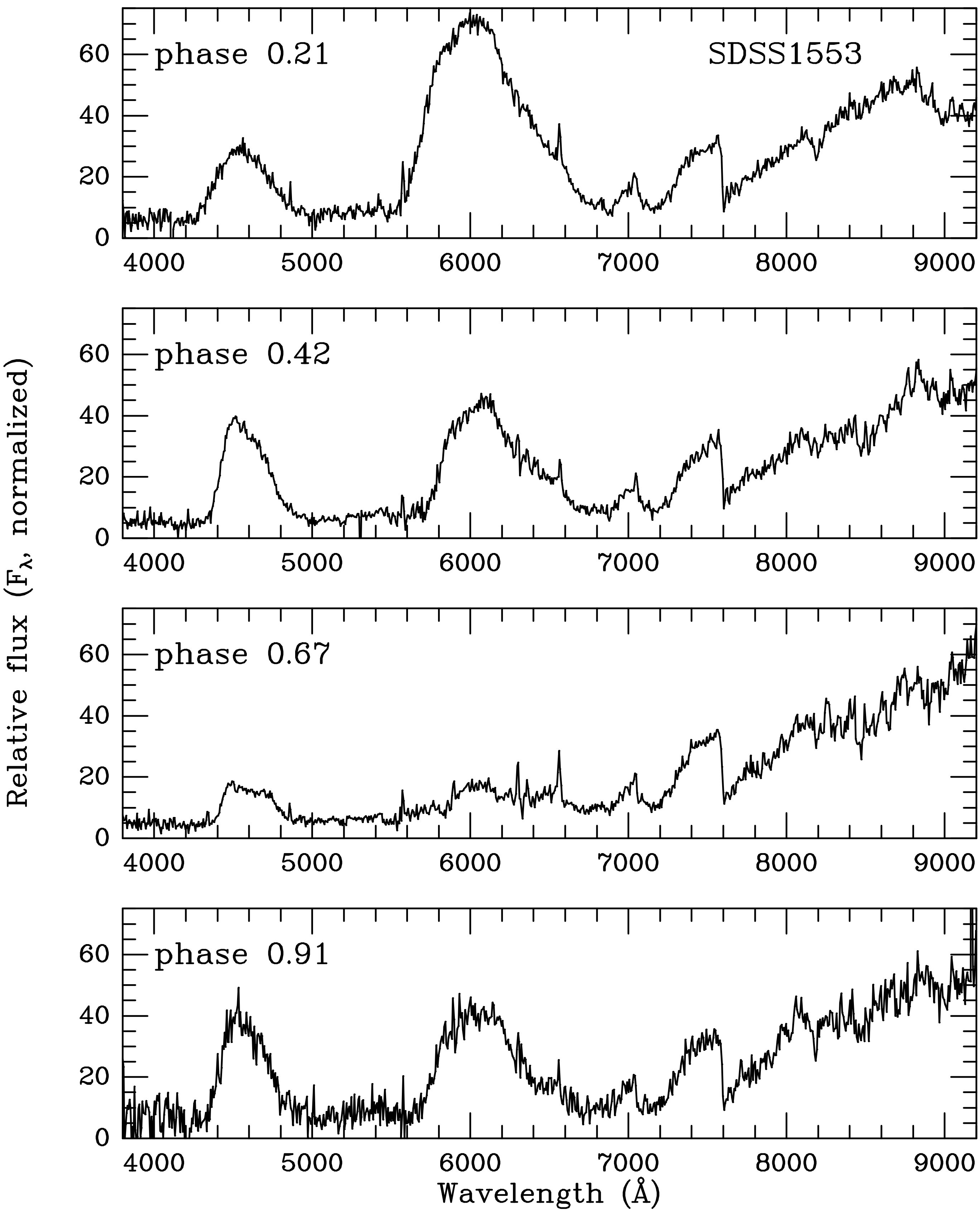
Fig. 3.— APO time-resolved spectra of SDSS1553 showing the changing amplitude of the cyclotron humps. Phasing is arbitrary, using the start time of the MRO photometry (JD2452164.73522). Spectra (top to bottom) were obtained on Sept. 3, 12, 10 and 4. To facilitate comparison of data obtained with different transparency/seeing conditions, all spectra were normalized by setting the (mainly) M-star continuum just shortward of 7600Å to the common value of $F_\lambda \sim 35 \times 10^{-17}$ erg s^{-1} cm$^{-2}\mathring{A}^{-1}$.

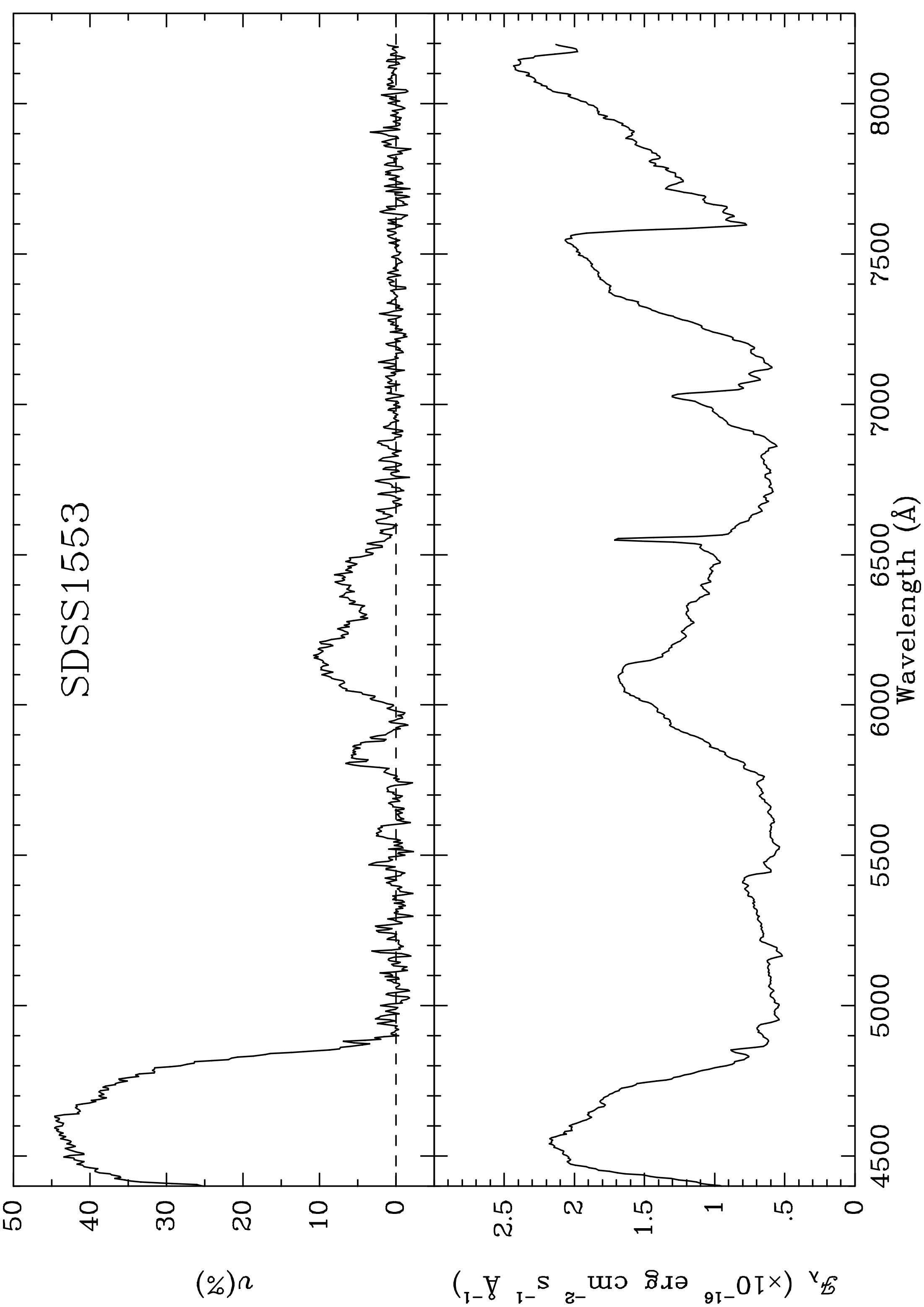
Fig. 4.— SPOL data for SDSS1553 showing the circular polarization (top) and total flux spectrum (bottom). Note the very high polarization of the broad emission features at 4600Å and 6200Å confirming their cyclotron nature.

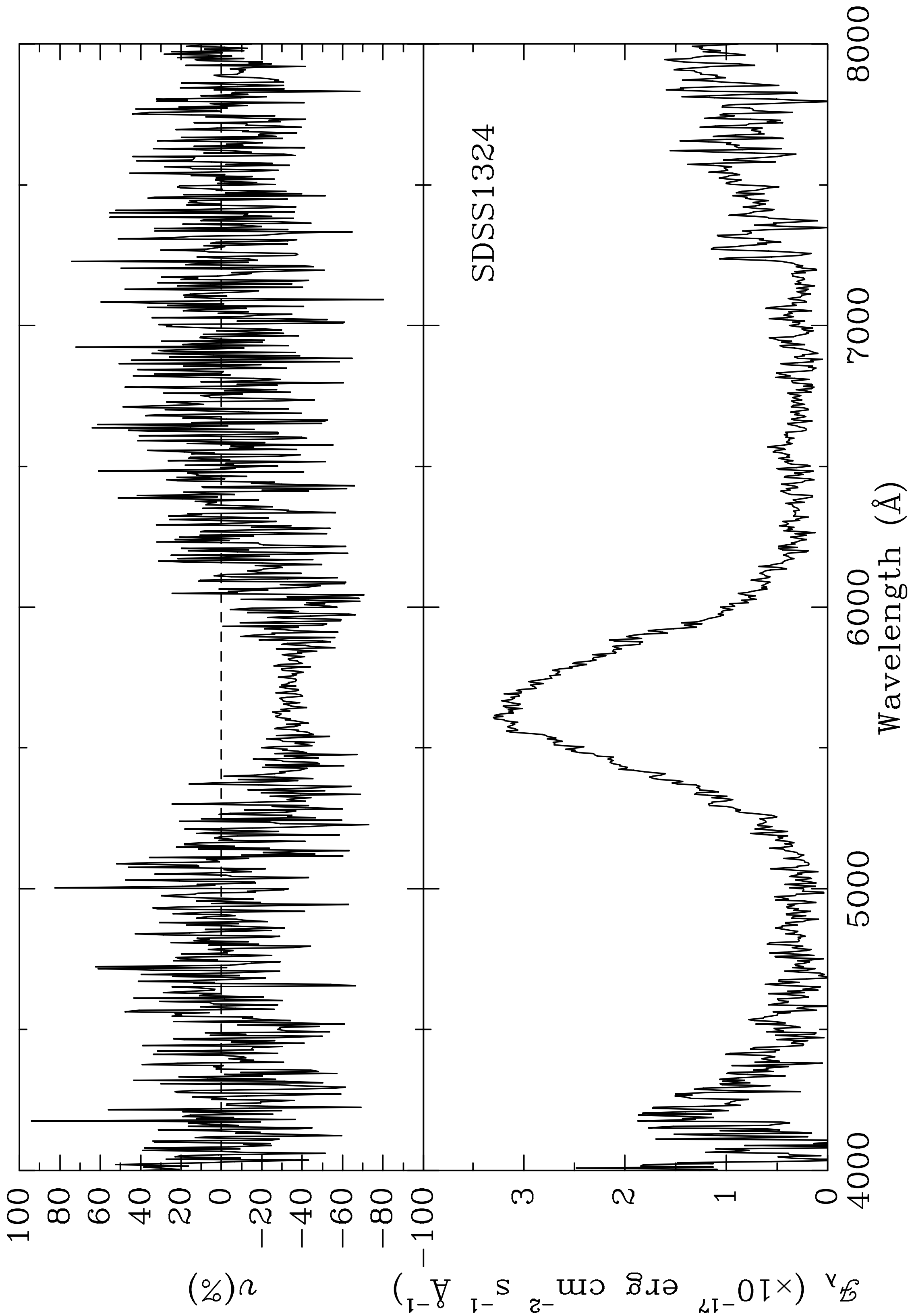
Fig. 5.— Phase-averaged SPOL data for SDSS1324 showing the circular polarization (top) and total flux spectrum (bottom). Again, the strong polarization confirms the cyclotron nature of the broad emission feature at 5700Å.


SDSS1553
SDSS1324
F_λ (x 10^{-17} ergs cm^{-2} s^{-1} Å^{-1})
WAVELENGTH (Å)

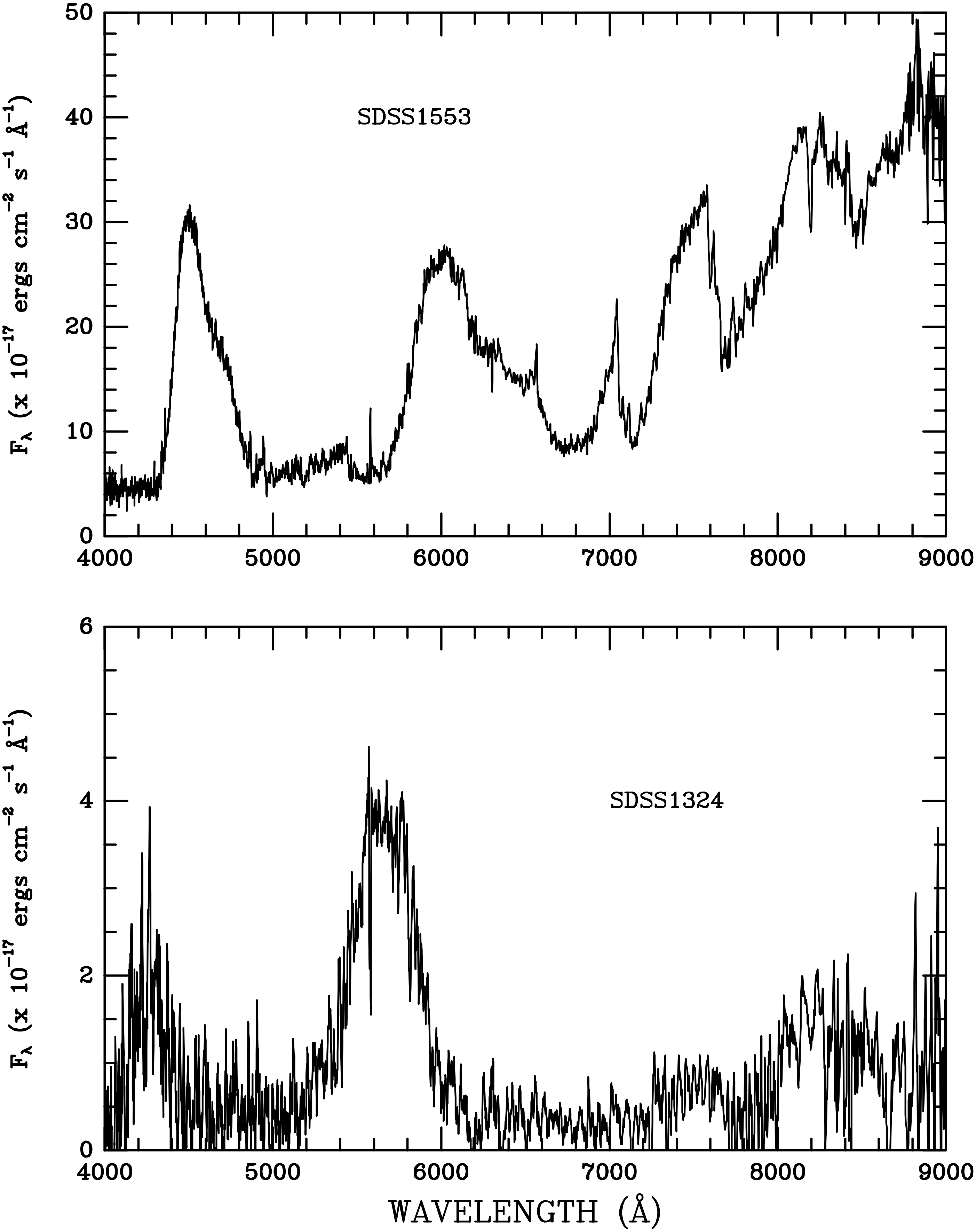

16
16.5
17
17.5
18
18.5
19
19.5
0
.2
.4
.6
.8
1
PHASE
MAGNITUDE
I
SDSS1553
Sloan r
R
V
B


phase 0.21
SDSS1553
phase 0.42
phase 0.67
phase 0.91
Relative flux (F_λ, normalized)
Wavelength (Å)
0
20
40
60
4000
5000
6000
7000
8000
9000

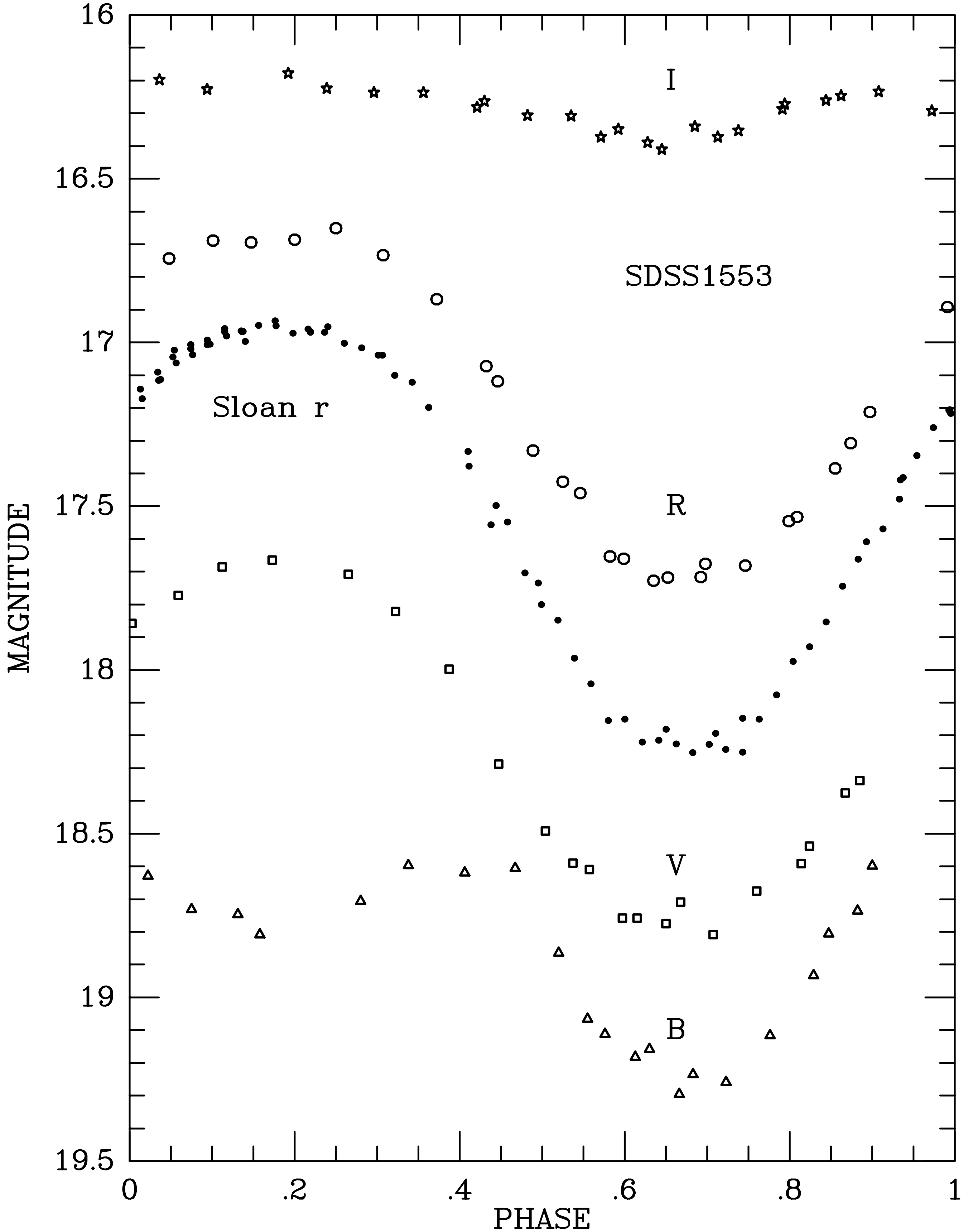

SDSS1553
v(%)
Wavelength (Å)
F_λ (×10⁻¹⁶ erg cm⁻² s⁻¹ Å⁻¹)



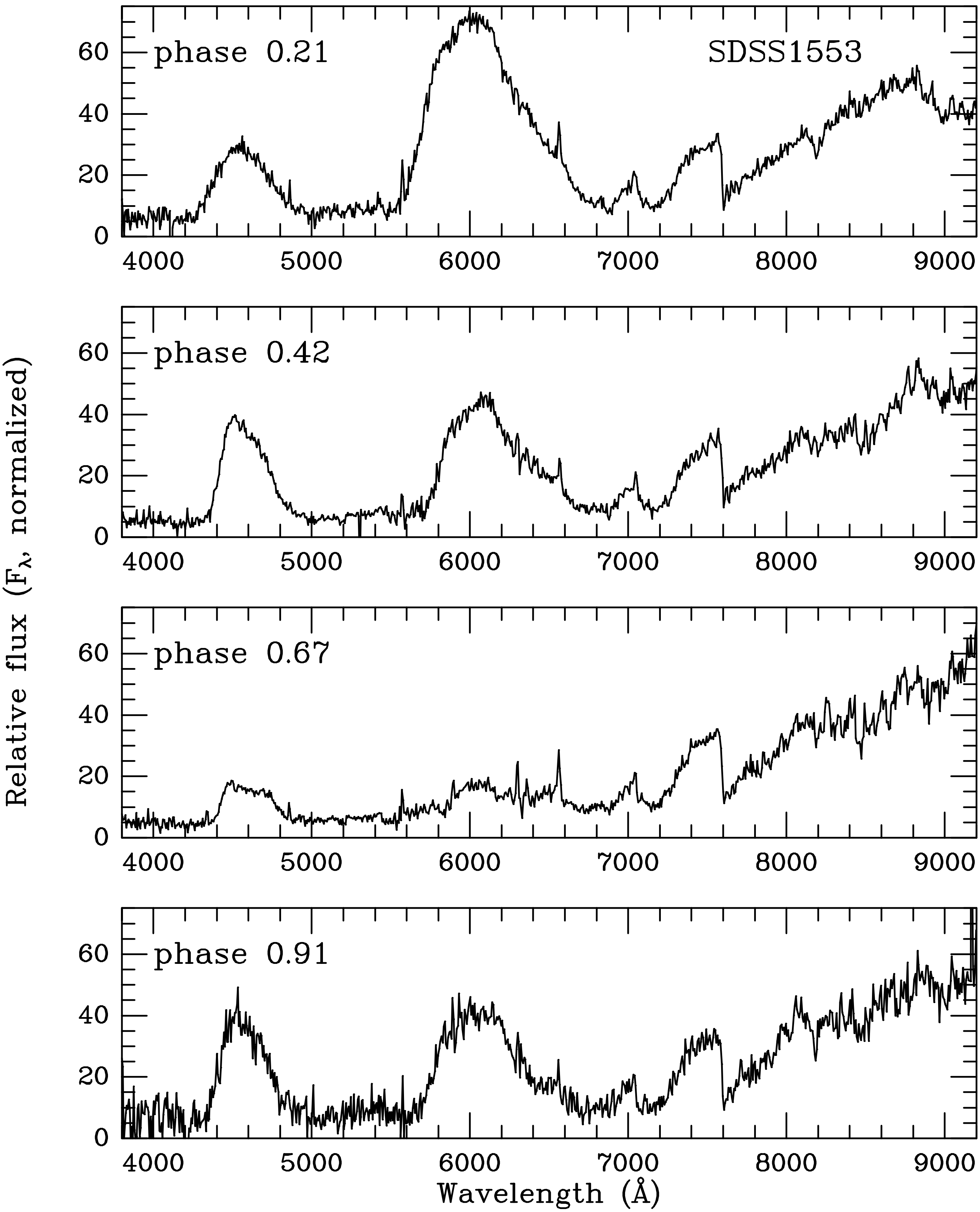
SDSS1324
Wavelength (Å)
4000
5000
6000
7000
8000
v(%)
100
80
60
40
20
0
−20
−40
−60
−80
−100
$\mathcal{F}_\lambda$ (×10^{-17} erg cm^{-2} s^{-1} Å^{-1})
0
1
2
3



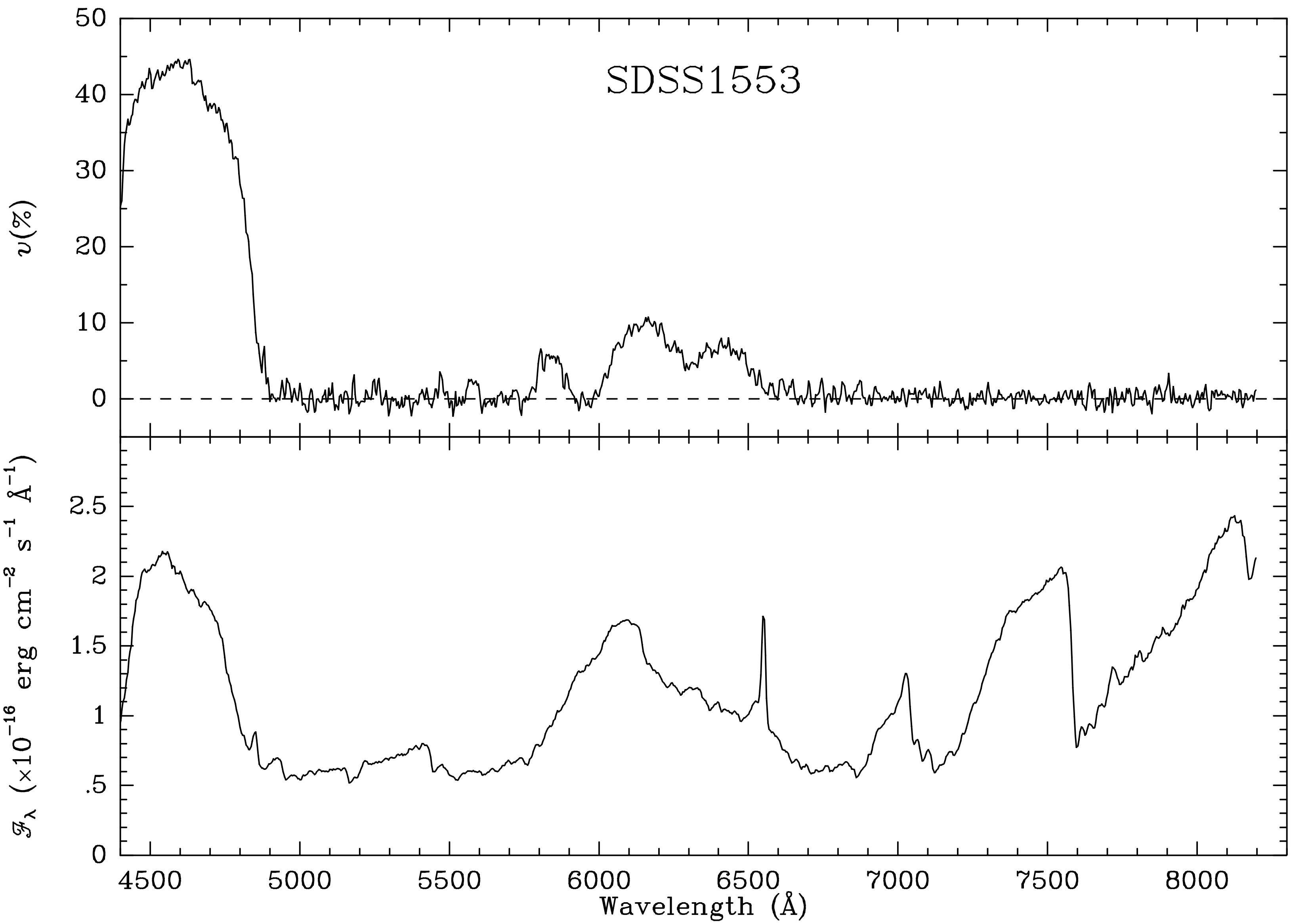
SDSS1553
SDSS1324
F_λ (x 10^{-17} ergs cm^{-2} s^{-1} $Å^{-1}$)
WAVELENGTH (Å)
0
10
20
30
40
50
2
4
6
4000
5000
6000
7000
8000
9000



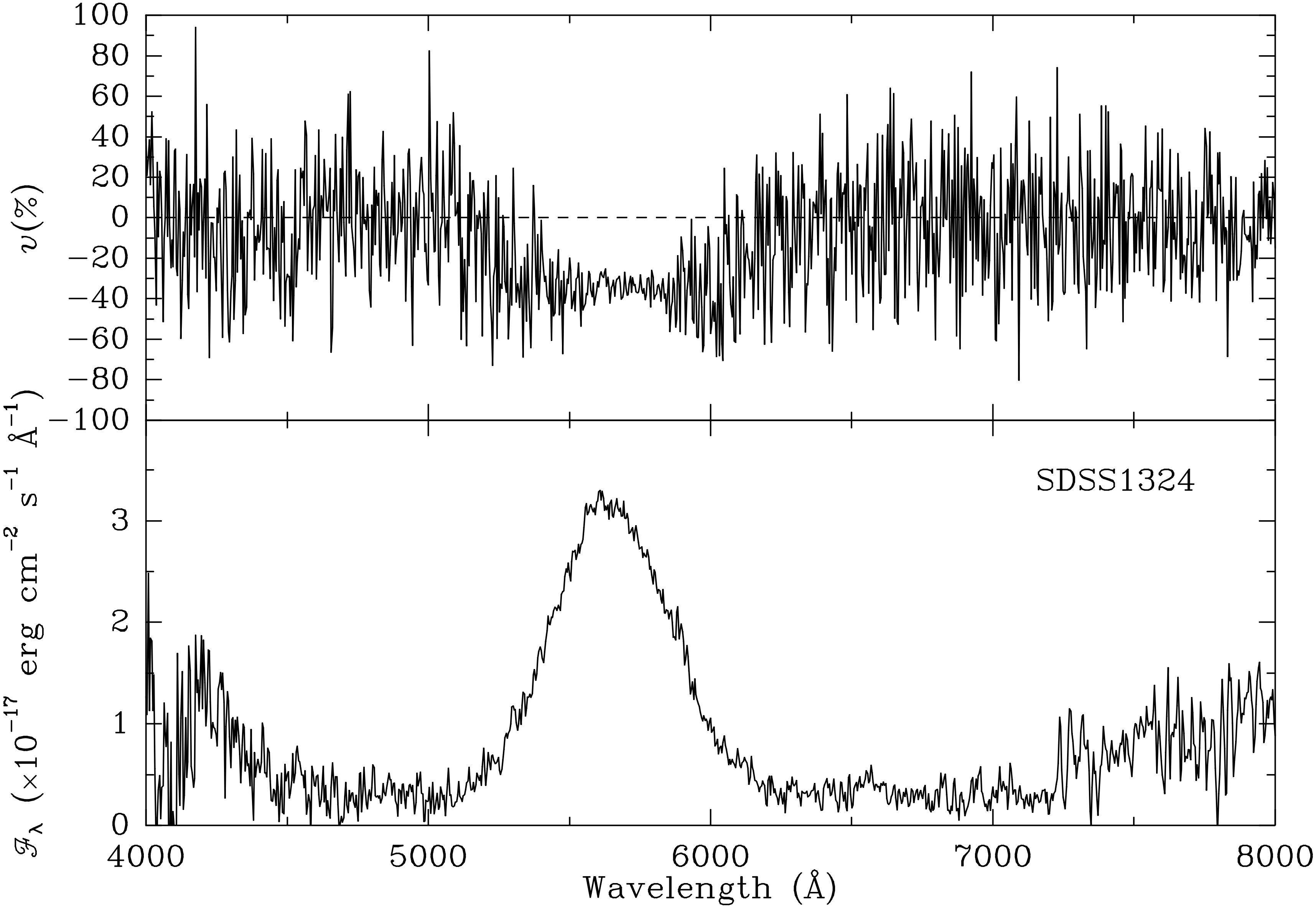
MAGNITUDE
PHASE
SDSS1553
I
R
V
B
Sloan r
16
16.5
17
17.5
18
18.5
19
19.5
0
.2
.4
.6
.8
1



phase 0.21
SDSS1553
phase 0.42
phase 0.67
phase 0.91
Relative flux (F_λ, normalized)
Wavelength (Å)
0
20
40
60
4000
5000
6000
7000
8000
9000



SDSS1553
$v(\%)$
$\mathcal{F}_\lambda$ ($\times 10^{-16}$ erg cm^{-2} s^{-1} Å^{-1})
Wavelength (Å)



SDSS1324
v(%)
Wavelength (Å)